Advanced Wafer Bonded Power Devices

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Outline

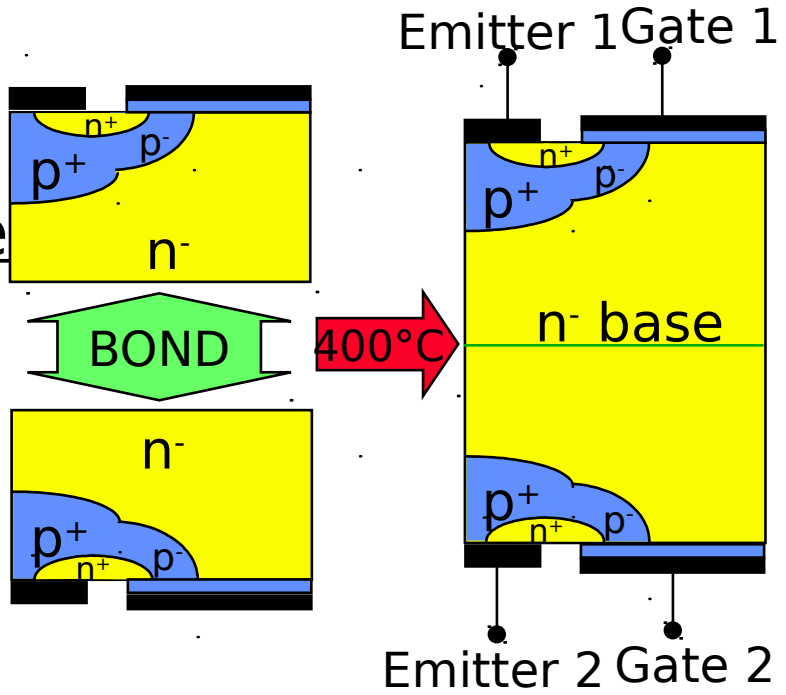
- Motivation
- Double-Side IGBT **Static Characteristics**
- Double-Side IGBT **Turn-Off Characteristics**
- Operation of Double-Side IGBT as Free Wheeling Diode to Reduce **Turn-On Loss**
- Manufacturing/Packaging Status
- Summary

Double-Side Power Device Technology Development

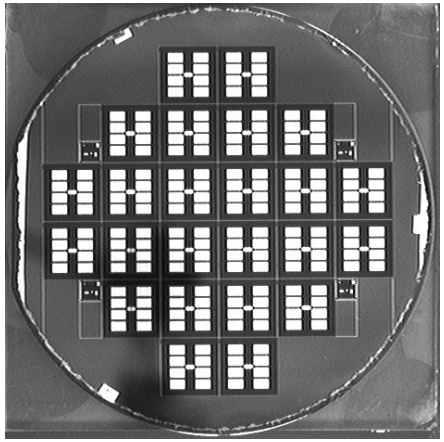
- Objective:
  - Demonstrate high voltage (3300V and 6500V) DIGBT modules with significantly reduced turn-off and turn-on loss
- Approach:
  - Purchase commercial high voltage IGBT wafers and fabricate high voltage double-side power devices devices utilizing wafer bonding
  - Commercial supplier:
    - Dynex 3300V IGBT
    - Dynex 6500V IGBT

Double-Side IGBT Fabricated by Direct Wafer Bonding

- Utilize very low temperature Wafer Bonding (≤400°C) afte IGBT fabrication
- Utilize commercial high voltage IGBT wafers (Dynex)
  - Optimized for DIGBT

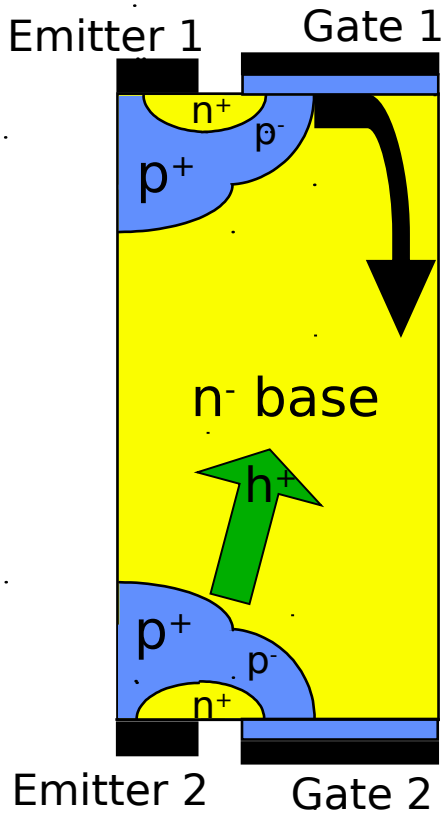


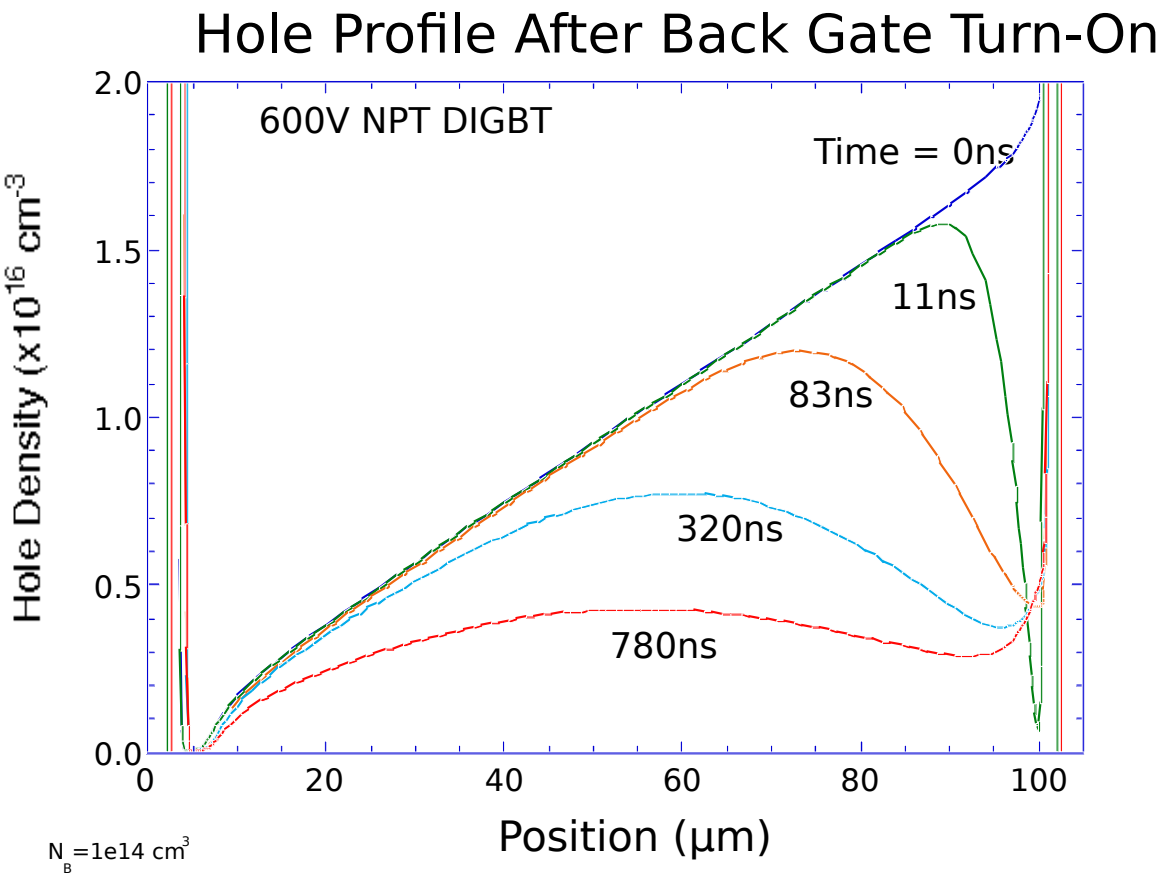
Dynex 6500V IGBT Wafer



Hole Distribution Following Back Gate Activation

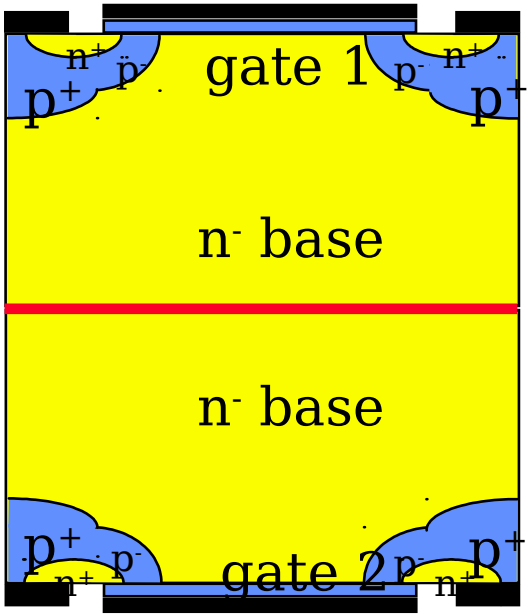
- Employ backside MOS gate to improve turn-off and turn-on loss
- Back gate shorts N-base to P+ emitter to stop hole injection
- **Turn-off loss is proportional to stored charge in base and especially the charge near the anode**



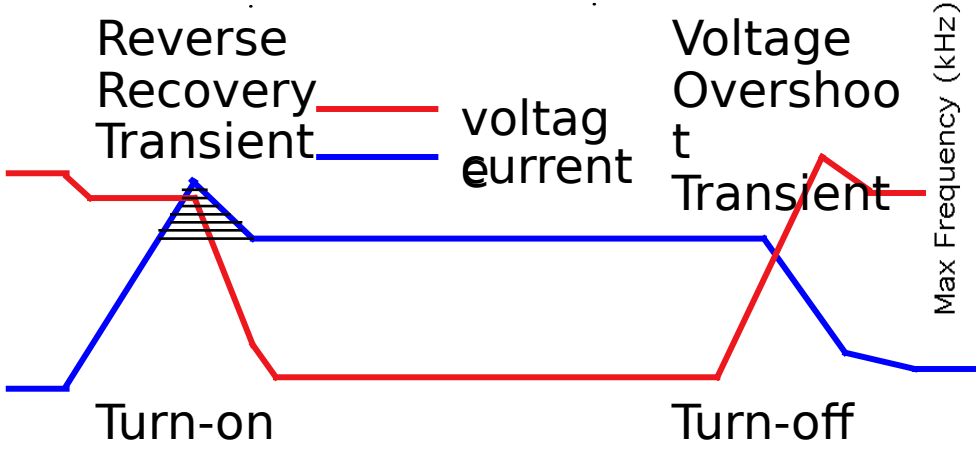


NRL Double-Side IGBT

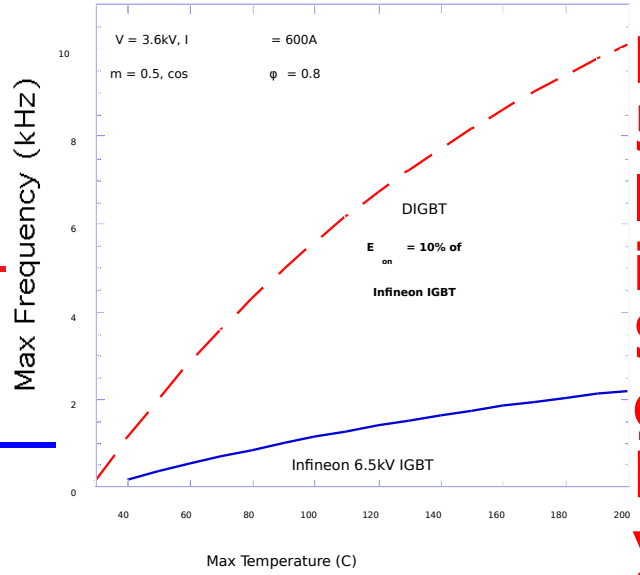
Double-Side IGBT



- ≈ 8x reduction in turn-on loss
- 4x reduction in turn-off loss
- 40% reduction in conduction loss
- Free wheeling diode not required
- Reduced reverse recovery transient and voltage overshoot transient
  - Reduced EMI and insulation stress



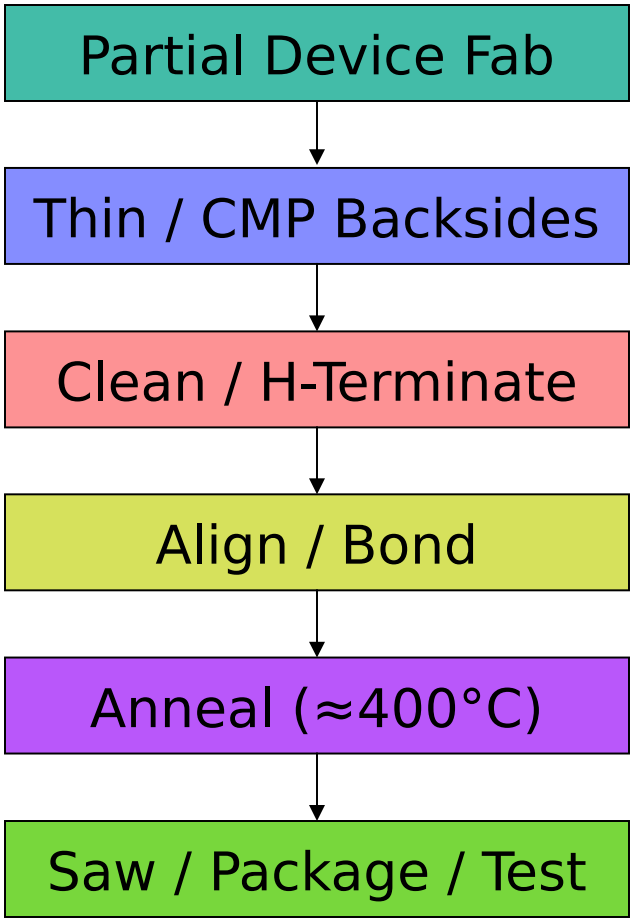
Power switch transient



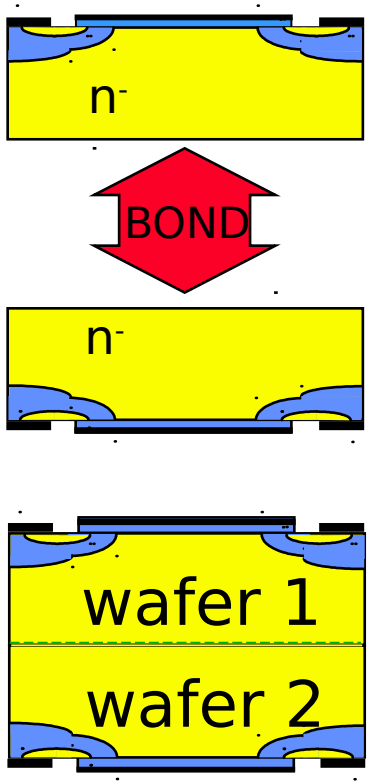
Project 5x Increase in Switching Frequency

Bonding Process

Basic Process

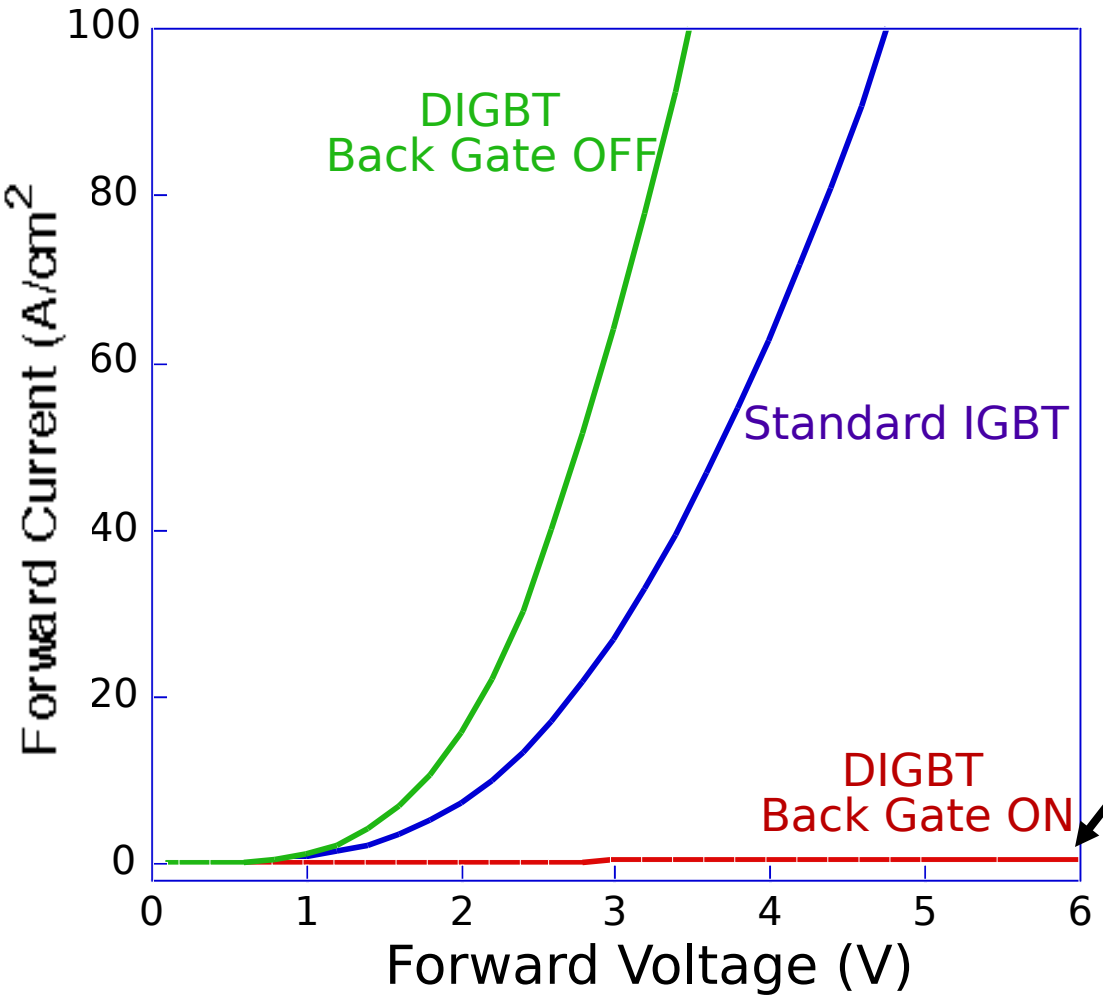


Double-Side, Double-Gate Insulating Gate Bipolar Transistor (DIGBT)



DIGBT Static Characteristics

Simulated DIGBT Static Characteristics

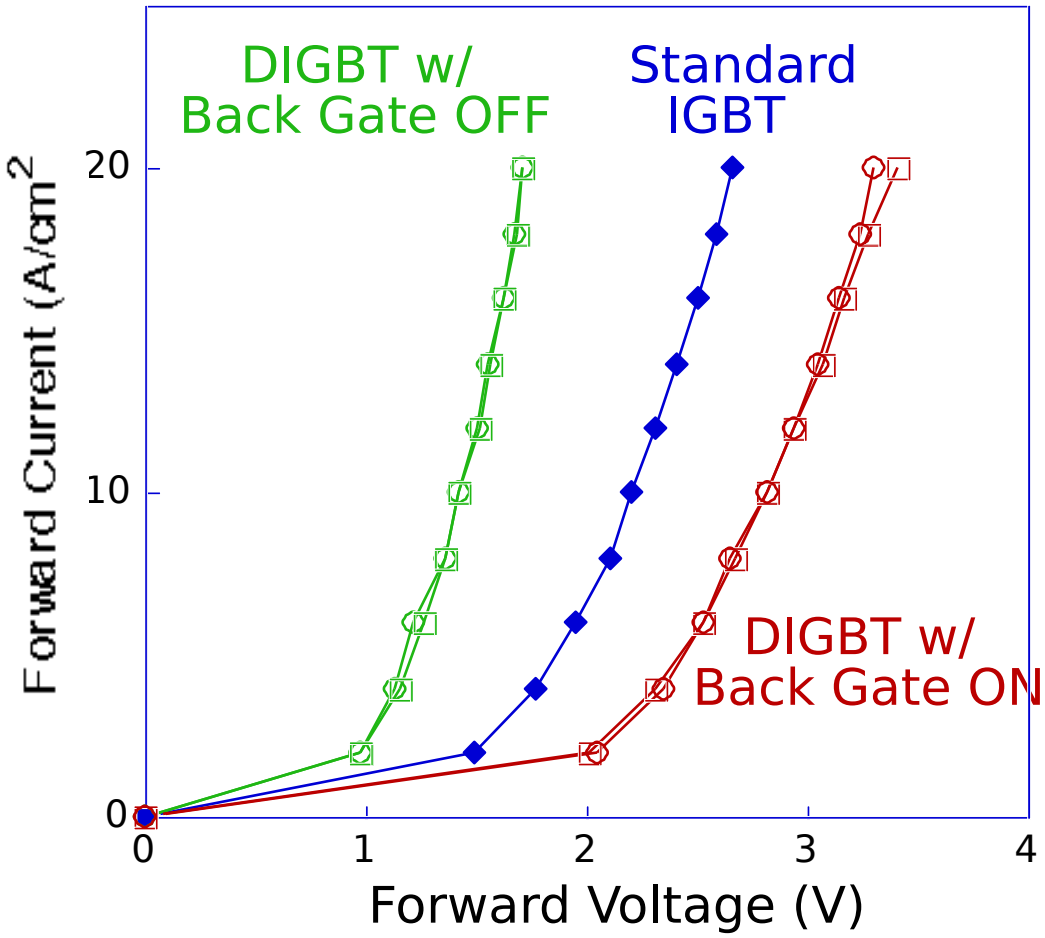


- Reduced DIGBT forward drop due to P-well hole injection
- DIGBT switches to MOSFET mode with back gate enabled
- Bi-Directional

MOSFET Mode

Early DIGBT Static Characteristic Experimental Results

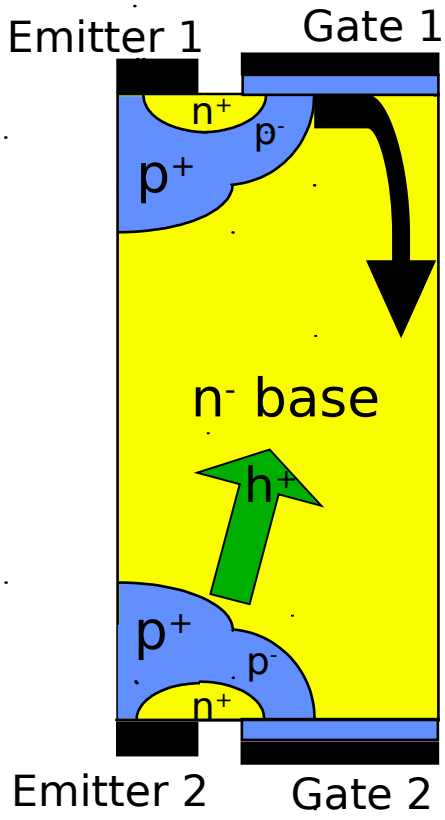
Measured Forward Drop



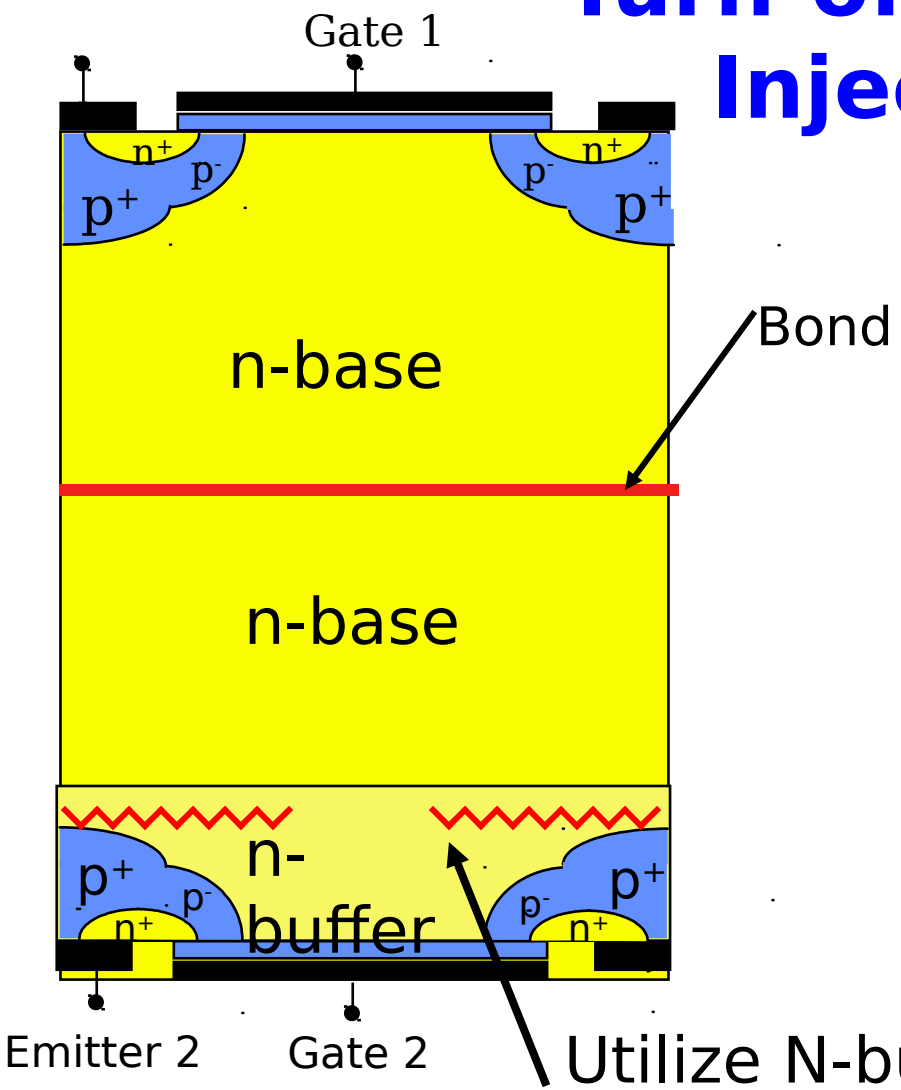
- Observe 40% lower forward drop at 20 A/cm^2 over reference device
- Pure MOSFET mode not observed
- Concluded that there are extraneous sources of hole injection on the backside

Approach to Eliminate Extraneous Backside Hole Injection

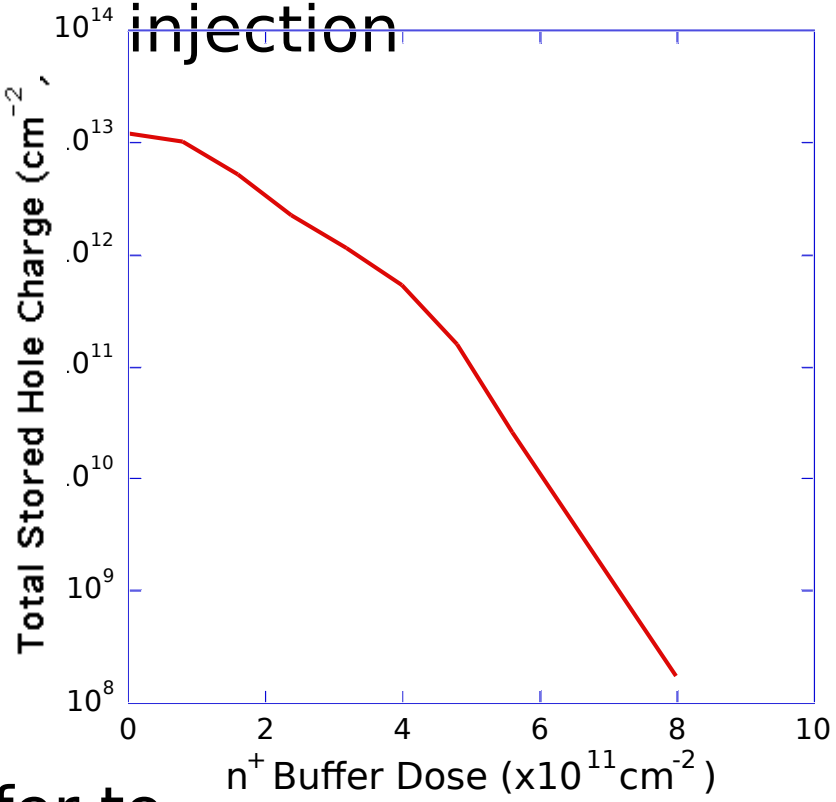
- Simulations ignored extraneous hole injection sources not controlled by back gate:
  - Field termination
  - P^+ diffusions under gate runners
- Recent DIGBT process runs eliminate extraneous backside hole injection by
  - Eliminating field termination
  - Eliminating P^+ gate runner doping
  - **Implement N-buffer on backside**



Utilize N-buffer for Turn-off of Hole Injection

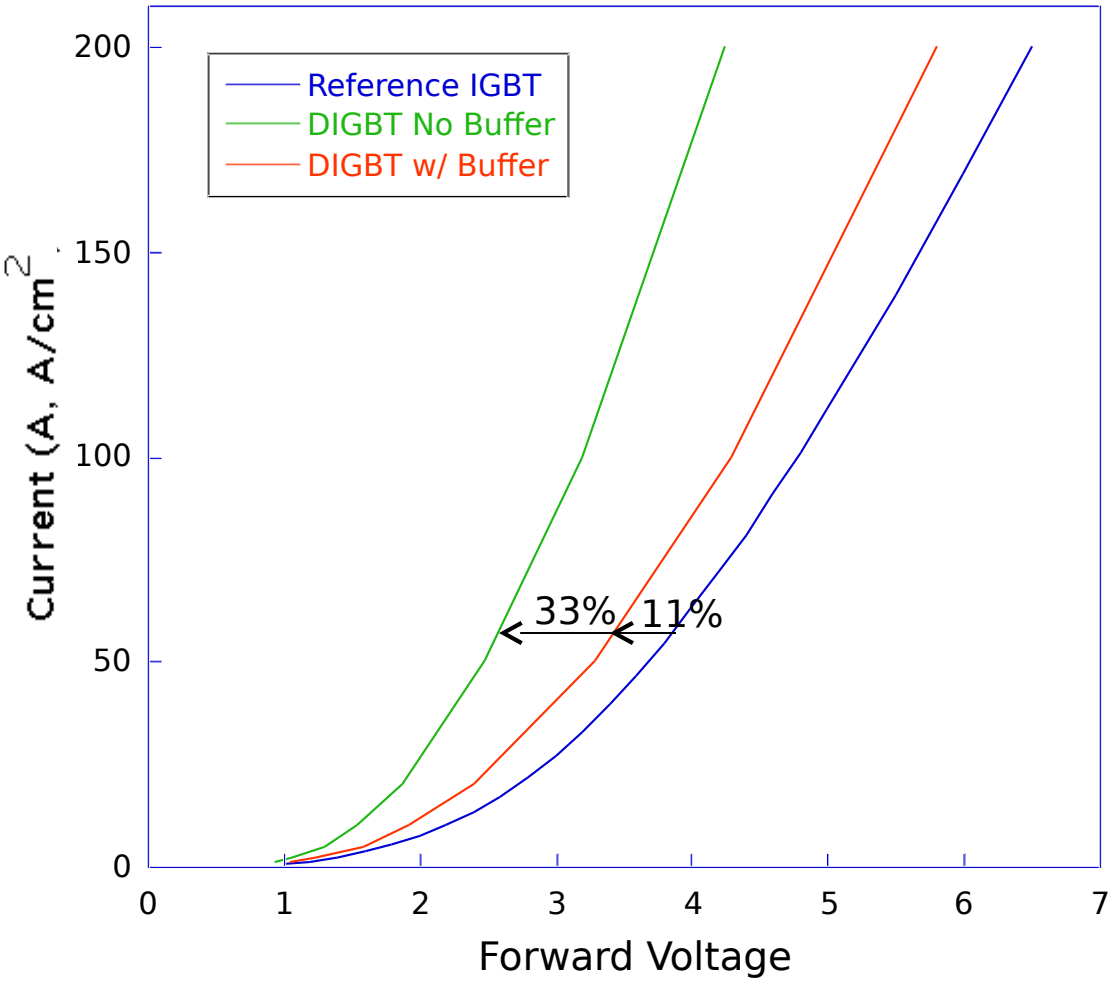


Buffer dose required to stop hole injection

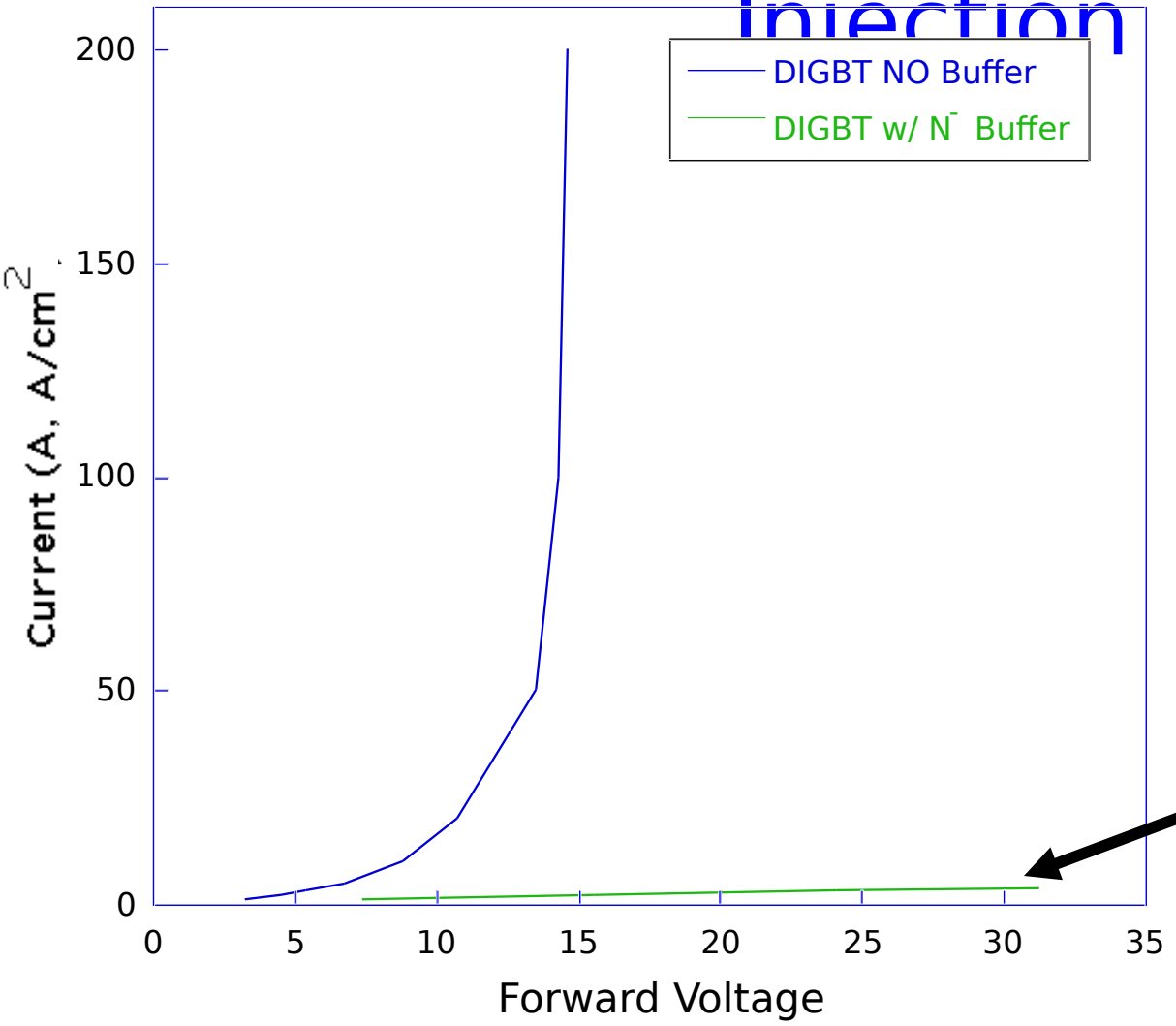


Utilize N-buffer to achieve complete turn-off of hole injection

Recent Experimental Results: DIGBT Forward Drop Comparison with and without N^- Buffer



Effect of N^- Buffer on Eliminating Extraneous Sources of Hole Injection

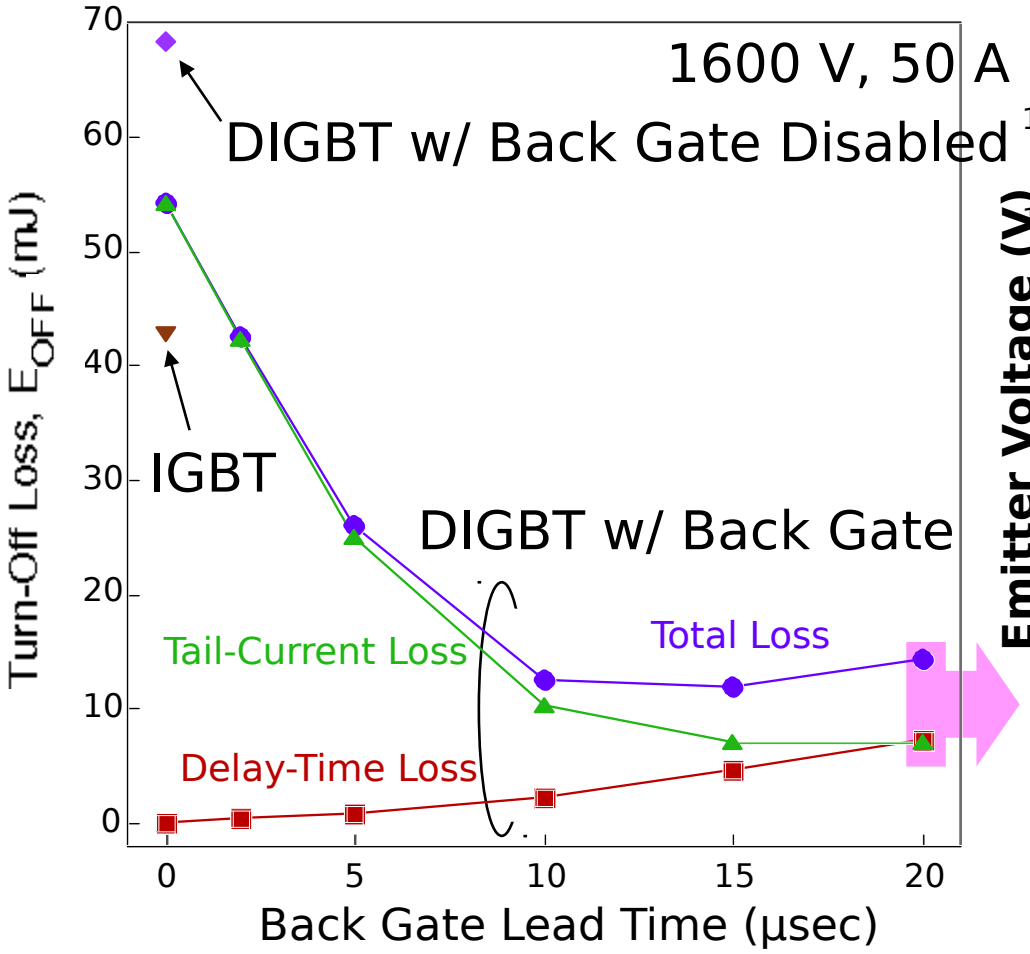


MOSFET Mode Achieved

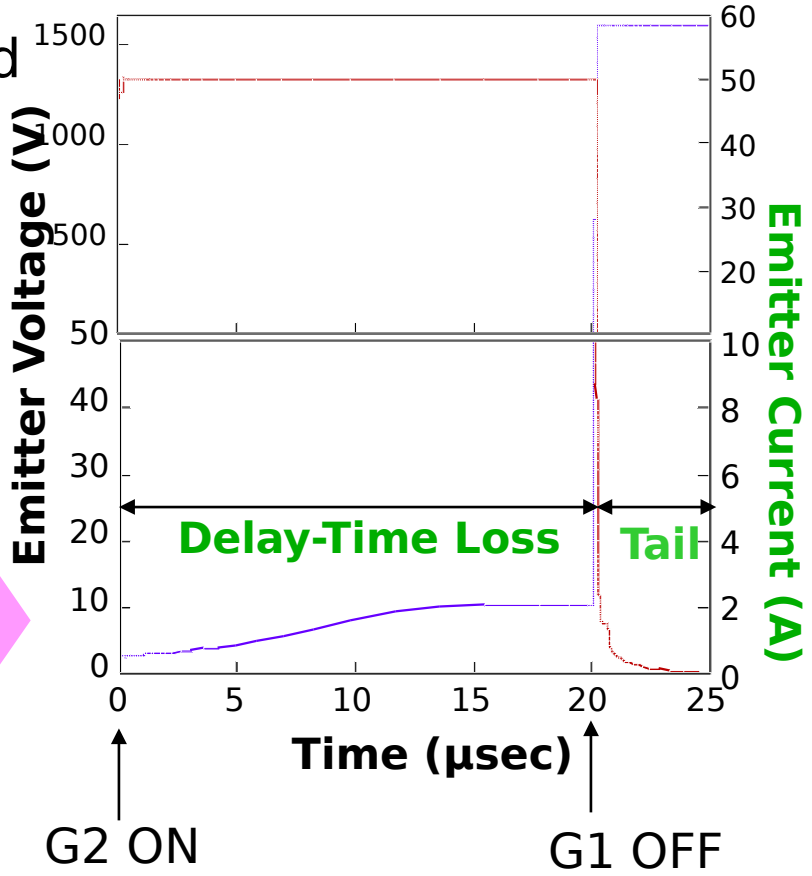
DIGBT Transient Characteristics

Double-Side IGBT Simulation (Non-Punch Through NPT Design)

- Simulation predicts ≈ 4x reduction in turn-off loss compared to single-side IGBT

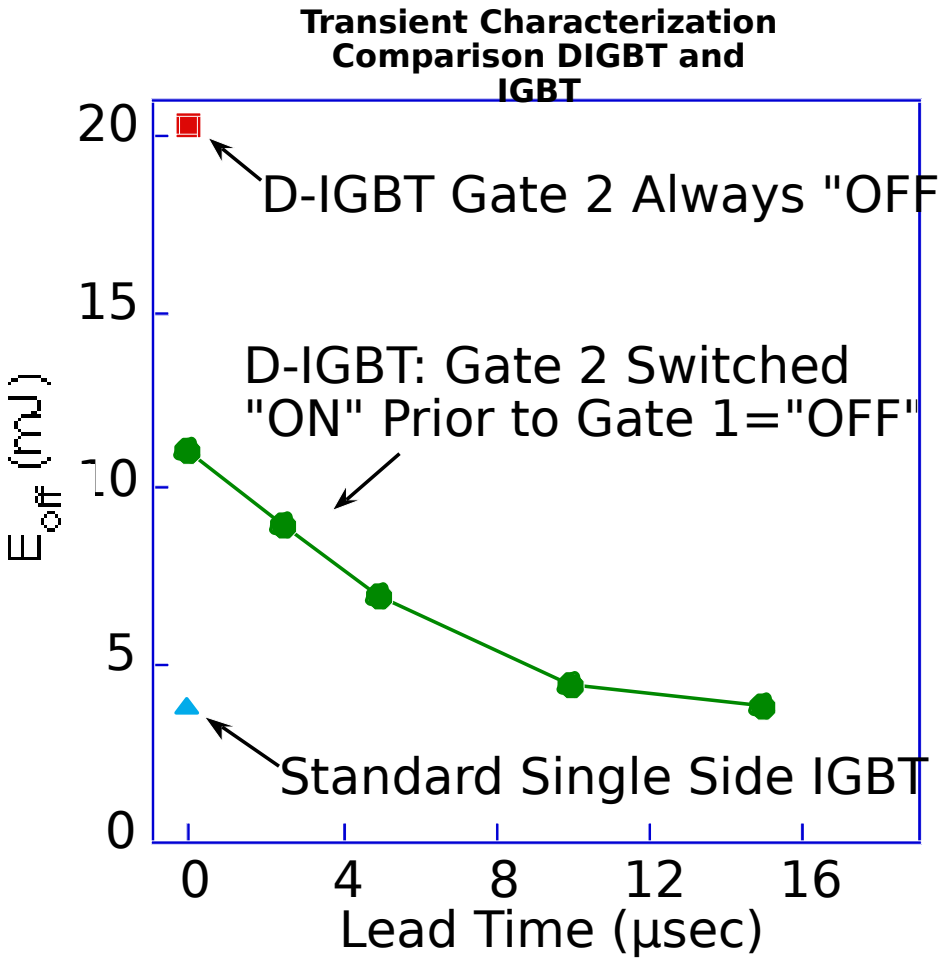


Switching Waveform



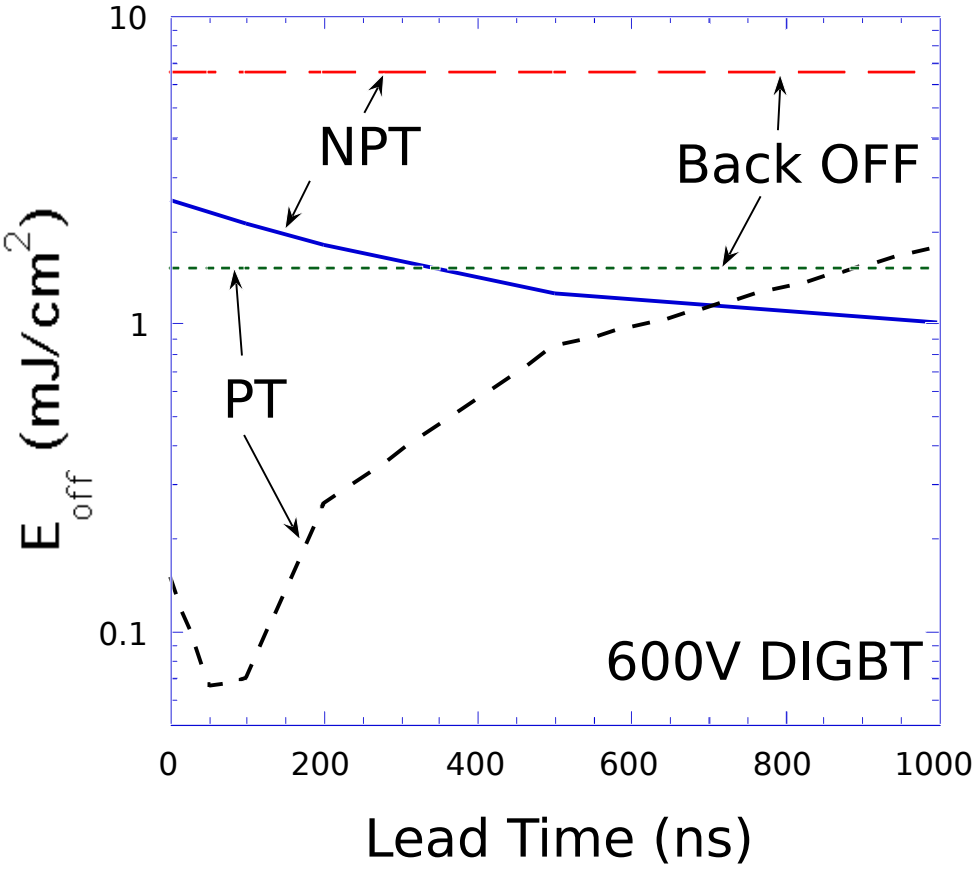
Double-Side IGBT Transient Experimental Measurements

- Optimum timing of back-gate provided 5X reduction in turn-off loss compared to back-side DMOSFET always off



Simulation of Turn-off Loss for 600V DIGBT

- Non Punch Through (NPT) Design:
  - Factor of 4-7 reduction for DIGBT compared to IGBT
- Punch Through (PT) Design:
  - Factor >10 for DIGBT compared to IGBT



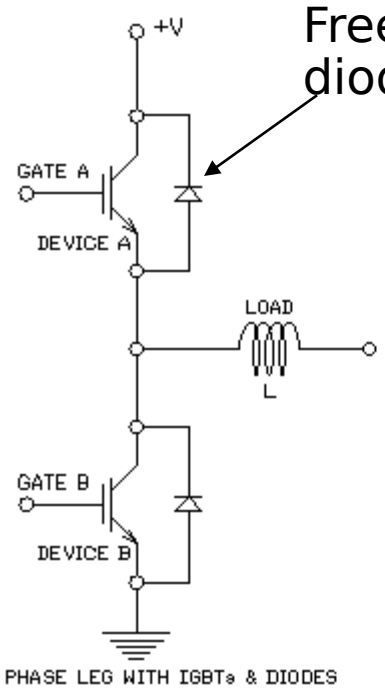
Punch Through (PT) Design has N- Buffer at DIGBT Backside

Observations:

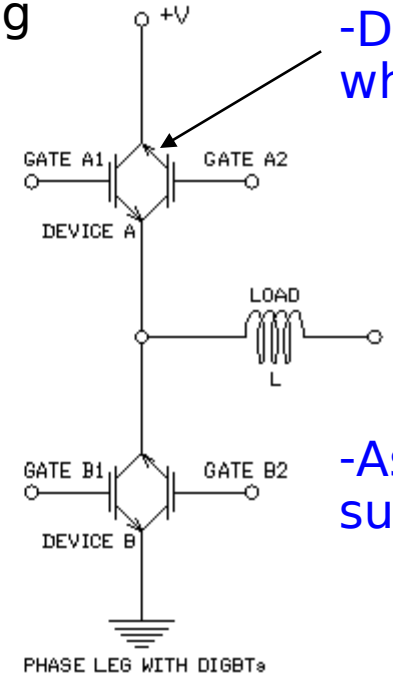
- Punch Through (PT) allows DIGBT to enter **MOSFET Mode** during turn-off
- Punch Through (PT) has **thinner silicon** for reduced hole storage in N- base

DIGBT Operated as Free Wheeling Diode to Reduce Turn-On Loss

Double-Side IGBT Phase Leg



Free wheeling diode



-Does not require free wheeling diode

-Reduced turn-on loss

-Reduced EMI

-Higher current per module

-Asymmetric DIGBT is suitable

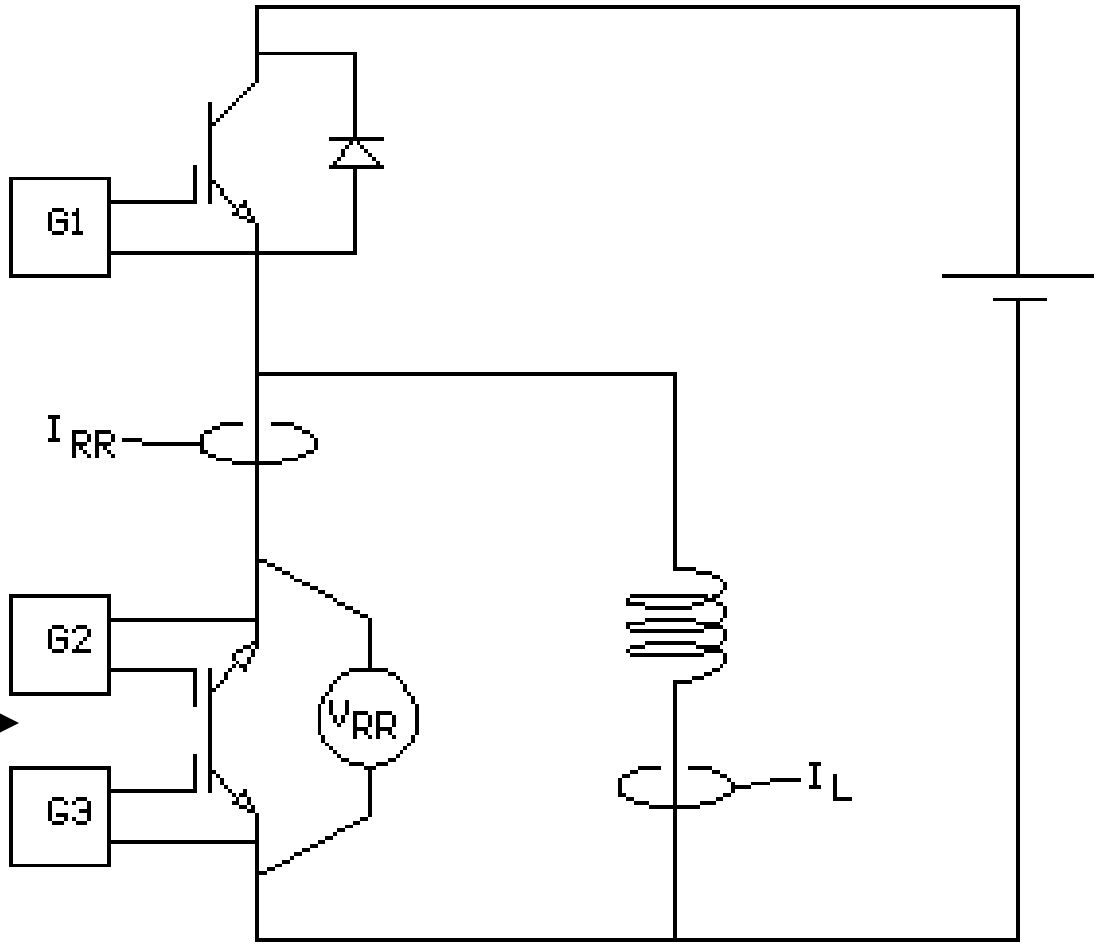
≈40% thinner silicon for reduced turn-off loss

Conventional phase leg

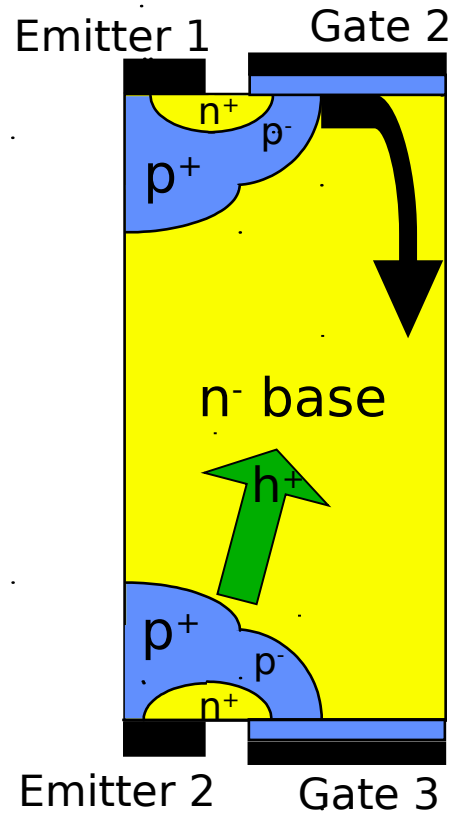
DIGBT phase leg

Experimental Test Set-Up for DIGBT Operating as Free Wheeling Diode

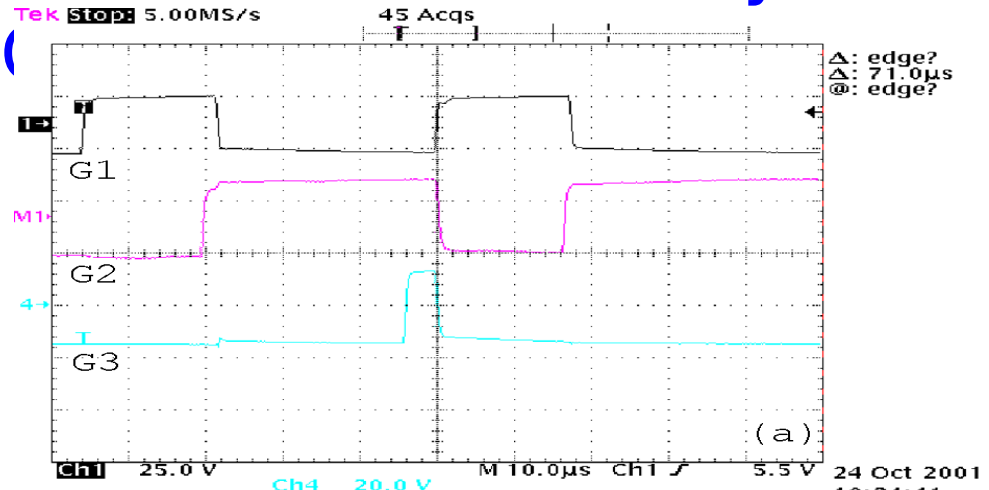
Double-Side IGBT Acting as Free Wheeling Diode

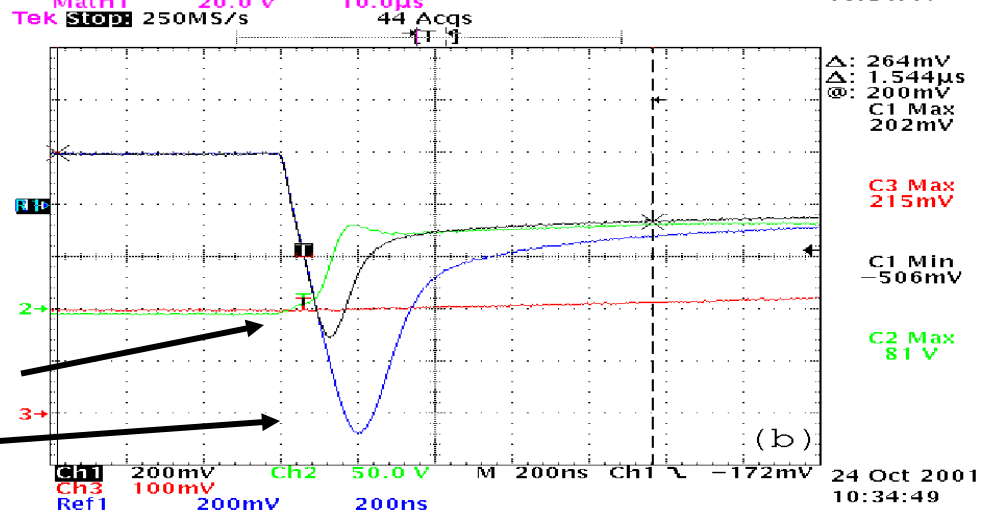


Clocking DIGBT As Free Wheeling Diode to Reduce Reverse Recovery



Reduced Peak Recovery Current Baseline Waveform

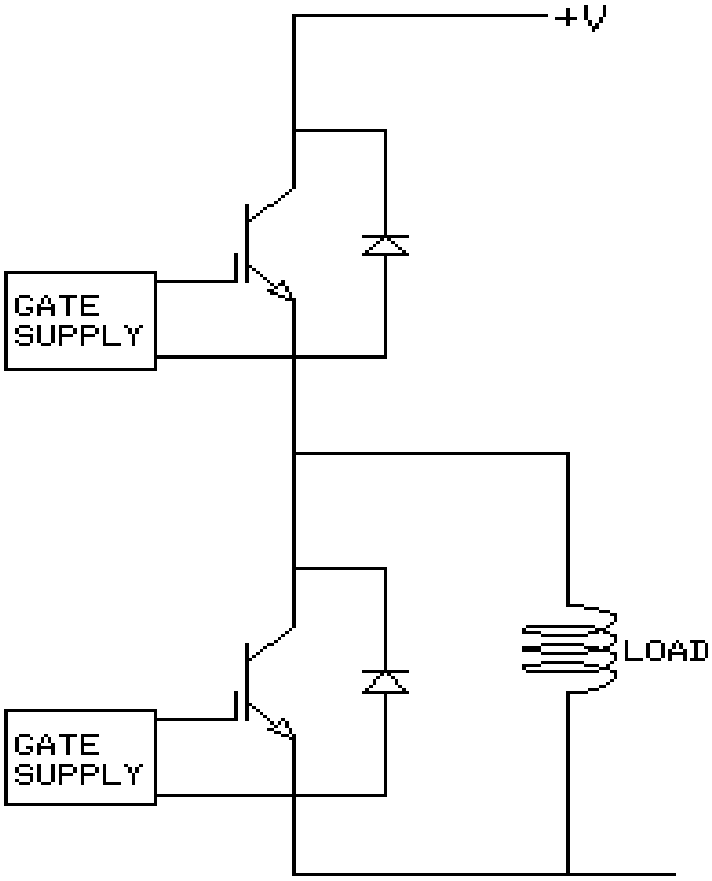




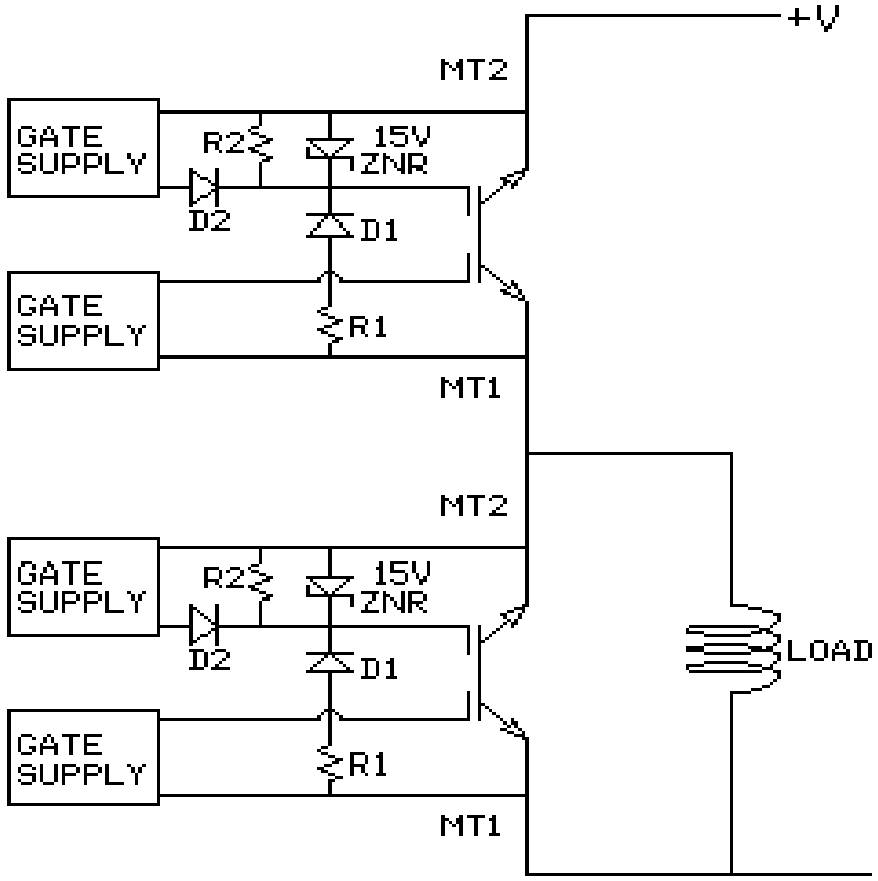
Clock Gate 3 to stop hole injection ≈ 4µs prior to turn-on of IGBT

- 50% reduction in peak reverse recovery current
- ≈75% reduction in reverse recovery charge

Double-Side IGBT Phase Leg with Protection Circuit



PHASE LEG WITH IGBTs & DIODES



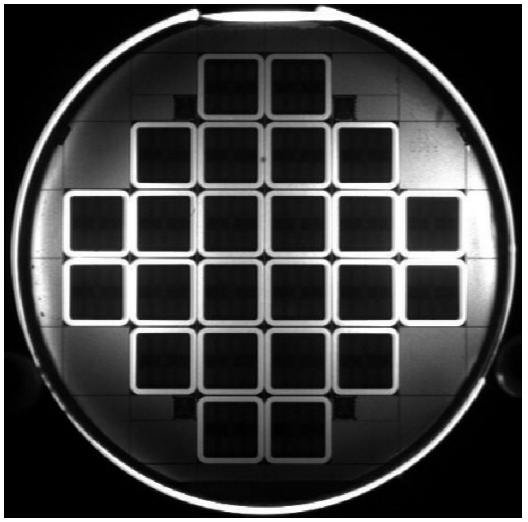
PHASE LEG WITH DIGBTs
WITH REVERSE-BIAS PROTECTION

Manufacturing Status and Yield

Developed Void Free Wafer Bonding Manufacturing Technology

Demonstrated 63% yield (>2kV blocking & good gates)

Each DIGBT wafer is ≈ $2K



Infrared Transmission Image showing void free wafer bonding

Phase Leg Estimation

Four 6.5kV switches required per each three-level 4160Vac phase leg

Each DIGBT wafer (≈15 good die @ 70A) can produce ≈ 1.0MVA 4160 Vac phase leg

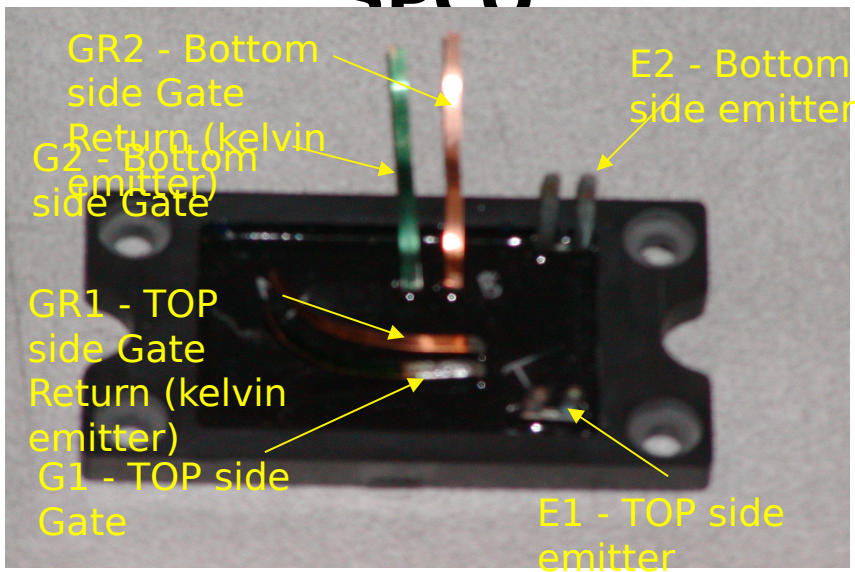
20MVA requires ≈ 20 DIGBT wafers @ 63% yield

20MVA requires ≈ $40K + Packaging

Packaging Status

Double-Side DIGBT ThinPack Package at

SPCO

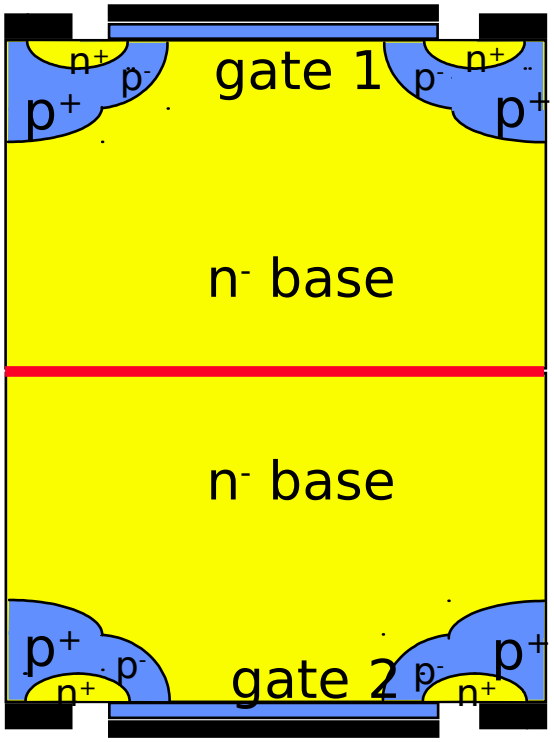

GR2 - Bottom side Gate Return (kelvin emitter)
E2 - Bottom side emitter
G2 - Bottom side Gate
GR1 - TOP side Gate Return (kelvin emitter)
G1 - TOP side Gate
E1 - TOP side emitter

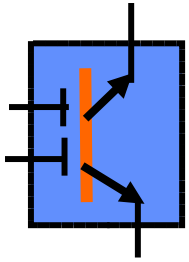
- Have recently packaged half-bridge modules
- Solderable metal and Packaging related issues are currently the key issues for DIGBT technology

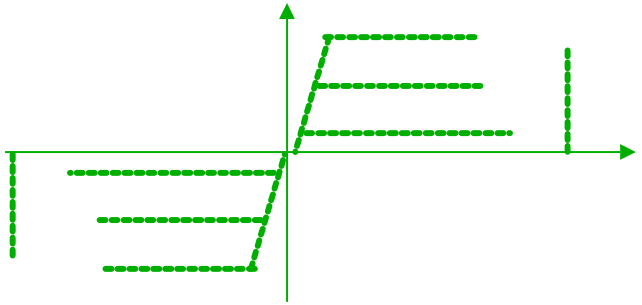
Double-Side IGBT can be implemented as Symmetric Switch

- four quadrant operation
- ideal power switch

Double-Side IGBT







Impact

- Matrix-converters
- Soft switching
- Solid-state relay

Summary

- Have developed method to achieve “MOSFET Mode” during turn-off
- DIGBT provides approximately 4x reduction in turn-off loss for non-punch through design and may provide greater reduction for “MOSFET Mode” turn-off
- DIGBT operating as free wheeling diode improves turn-on characteristics of a DIGBT
  - 50% reduction in peak reverse current
  - ≈ 75% reduction in reverse recovery charge
- Describe an approach to protect DIGBT Phase Leg from improper clocking
- Demonstrated very low temperature direct wafer bonding technique for realization of double-side IGBT
  - Manufacturable process for near-term production of advanced IGBTs